Satellite Aerosol Detection in the NPOESS Era

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ABSTRACT

Agencies responsible for monitoring air quality have traditionally relied on ground-based measurements to detect and predict fine particulates while satellite data has been underexploited. By providing observations over large spatial domains (and in some cases, vertical information) not available from traditional monitoring stations, satellite data can aid in the detection, tracking and understanding of aerosol transport. Satellite aerosol data can also be used quantitatively to initialize and validate air quality models. Just as new satellite data assimilation techniques are at the forefront of weather prediction science, satellite aerosol data assimilation should become an integral part of regional or local haze predictions. The detection of fine particulate matter (PM2.5) from the ground or space is technologically challenging; however, there are numerous satellite sensors that already provide some type of aerosol detection capability and future sensors promise significant enhancements. Each type of satellite system has strengths and weaknesses for aerosol detection. Typically sensors aboard polar orbiters yield high spatial resolution, but satellites passes are infrequent, particularly for science missions. Aerosol optical thickness derived from geostationary data yields frequent refresh at the expense of global coverage. Most satellite aerosol retrievals provide total column aerosol information, though some state-of-the-art science missions also provide vertical profiles.

The future generation National Polar-orbiting Operational Environment Satellite System (NPOESS) will become operational in 2010. NPOESS merges today's science environmental satellites and operational weather satellites into an integrated operational environmental observing system. It is a three orbit plane system that will provide significantly improved data quality, frequent data refresh, and rapid downlink and ground processing that delivers products in less 30 minutes meeting both science and operational needs. The NPOESS VIIRS (Visible Infrared Imaging Radiometer Suite) will extend the aerosol measurements initiated by its heritage sensor, the Moderate Resolution Imaging Spectroradiometer (MODIS) that currently flies on EOS' Terra and Aqua satellites. The NPOESS Ozone Mapping and Profiler Suite (OMPS) will yield aerosol information through an interim step in the ozone retrieval process that corrects for aerosols. In addition, NPOESS will include an instrument dedicated to aerosol detection, the Aerosol Polarimetry Sensor (APS). Though air-quality agencies did not play a role defining original requirements for the baseline system, the NPOESS acquisition process is designed to allow involvement by the science and user community. Several avenues exist in which the air quality community can stay abreast of and even affect the development of the NPOESS sensors and data retrieval algorithms. The parallel development of techniques to assimilate satellite aerosol retrievals into mesoscale numerical models will be essential to fully exploit future satellite aerosol data in support of both regulatory and future operational forecasting of particulate matter.

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INTRODUCTION

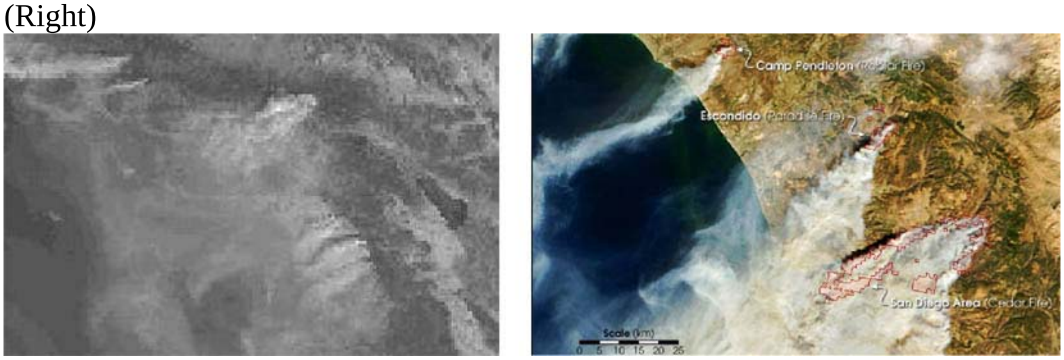
Aerosol particulate matter (PM), are tiny suspended solid particles or liquid droplets that enter the atmosphere from either natural or human (anthropogenic) sources. Particulate matter includes dust, pollen, black carbon (soot, smoke), and tiny liquid droplets of sulfuric acid, PCBs, oil, and various pesticides. The detection and prediction of atmospheric aerosols has always been important in traditional military and civilian weather applications. Dust storms in desert regions are detrimental to military operations. Aerosols impede visibility, a criteria weather parameter for civilian and defense aviation. Aerosols have taken on a new significance in recent years with anthropogenic sources contributing to visibility degradation of the nation's most coveted vistas and giving rise to numerous health problems. Recent studies have demonstrated that fine particulates, aerosols < 2.5μm (PM2.5), serve to transport and lodge toxic air pollutants deep in the lungs. Threats to Homeland Security also add a new dimension to the importance of predicting the dispersion of aerosols. Biological spores that could be released in a terrorist attack are on the order of fine particulates in size. Aerosols are also gaining notoriety in global warming research for their effects on the earth's energy balance. Some aerosols like sulfates cause a direct climate forcing by reflecting sunlight to space, cooling the atmosphere. For other aerosols, primarily those containing black carbon, which absorb some of the incident radiation, whether they heat or cool the atmosphere depends the surface albedo. Of comparable significance to the direct aerosol effects is their indirect effect through altering the cloud properties. The aerosols serve as additional cloud condensation nuclei (CCN) modifying the cloud microphysics and changing the cloud albedo, amount of precipitation, and the lifetime of the clouds. It is difficult to assess the climatic impact without knowledge of the aerosol characteristics including their concentration, size distribution and chemical composition. Uncertainty in aerosol science is one of the largest unknowns in predicting anthropogenic climate change. [1]

The climate community has been driving the need for improved satellite detection of aerosols. Observations of the global and vertical distributions of size, composition, physical and optical properties of aerosols are needed to determine whether the overall effect of aerosols enhances heating or cooling of the atmosphere. The spatial and temporal heterogeneity of aerosols means that realistically this can only be done from a satellite platform. Traditional weather applications have relied on ground based assessments of visibility, rather than determining specific aerosol properties. Surface networks that monitor air quality in the US, such as the State and Local Air Monitoring Stations (SLAMS) and National Ambient Monitoring Stations (NAMS), measure coarse particulates with diameters up to 10 μm in size (PM10) and the new National Ambient Air Quality Standard (NAAQS) for fine particulates requires the addition of monitors that measure PM2.5 as well. Sunphotometers in the NASA aerosol network known as AERONET AErosol RObotic NETwork (AERONET) (http://aeronet.gsfc.nasa.gov) are stationed at a number of sites around the world and represent the benchmark for passive ground-based aerosol measurements for climate research. However, the sparsity of ground-based measurements limits their utility in understanding climate impact, the transport of aerosols, or ambient detection for operational applications. Space-based measurements are beginning to be a valuable tool in the detection, tracking and understanding of aerosol transport by providing observations over large spatial domains, particularly in rural and remote areas where there are no ground-based measurements. Some satellite sensors also provide aerosol profile information not available from traditional monitoring stations. Satellite data can be used qualitatively (imagery and visualizations) to provide a regional view of aerosol transport, or quantitatively to initialize and validate weather, climate, and air quality models. This paper provides an overview of selected current and future space based aerosol monitoring missions followed by a brief discussion on the need to develop the capabilities to assimilate these valuable data sets into atmospheric modeling systems.

CURRENT AEROSOL SENSORS

Numerous satellite missions can retrieve aerosol information, primarily by detecting the fraction of the solar radiation that aerosols scatter a back to space. Qualitatively, aerosol transport events can be detected by visible inspection of imagery. Aerosols appear as diffuse gray areas in contrast to the brighter and more textured appearance of clouds. The Defense Meteorological Satellite Program Operational Line Scan (OLS) visible channel is used qualitatively in this manner to detect smoke and dust storms for military applications around the world. In near real time, the system delivers vivid imagery of dust storms blanketing the Iraqi desert and pinpoints smoke from oil fires that flare with terrorist activity. Even more impressive are the NASA EOS MODIS images of smoke and dust plumes. Though MODIS data distribution was not originally structured to meet operational timelines, both civilian and military weather centers have taken steps to access this imagery for operational use.

Figure 1. Wildfire Smoke plumes evident in both DMSP OLS (Left) and EOS MODIS (Right)



Quantitatively, aerosol optical thickness (AOT) can be retrieved from satellite detection of the solar-reflected radiance along with knowledge of the albedo of the underlying surface and the aerosol angular scattering (phase) function (which is strongly dependent on the aerosol size distribution and chemical composition). Aerosol models are generally employed in conjunction with the satellite data in AOT retrieval algorithms. The process is simplified over the oceans because the ocean surface has a relatively low and constant albedo. Retrievals are more difficult over land surfaces because of the complex and variable radiative properties, though various algorithms have been developed to extract

AOT over land as well. Aerosol size distribution information can be inferred from the spectral dependence of aerosol optical thickness. More sophisticated passive techniques that exploit multispectral, multiangle, and/or polarization information have evolved that can provide a variety of aerosol parameters over both land and oceans for cloud-free, daytime conditions. Satellite sensors that can deliver aerosol information are categorized below as: those that rely primarily on measurements of solar backscatter in visible and/or near infrared; ozone sensors that detect ultraviolet absorption and backscatter; polarimeters that exploit the polarization information in the backscattered signal; and active lidar systems. Sensors within each of these categories can also use multispectral and/or multiangle measurement techniques.

Vis/IR Solar Backscatter Sensors

Operational satellite remote sensing of tropospheric aerosols used to be mostly limited to over ocean areas using the NOAA Advanced Very high Resolution Radiometer (AVHRR) on the Polar-orbiting Operational Environment Satellites (POES). NOAA/NESDIS routinely generates global aerosol optical depth over ocean during the daytime from the AVHRR solar reflectance bands centered at 0.63, 0.83, and 1.61 mm. The AVHRR provides high spatial resolution, but calibration uncertainties can impact accuracy and the limited spectral resolution constrains its ability to distinguish the land and sea contributions to the observed signal. [2]

While polar orbiting data provides global coverage, geostationary satellites have the advantage of more frequent data. The GOES Imager measures atmospheric radiance at 5 wavelengths: 3 in the Infrared, one in the near-infrared, and one in the visible. In collaboration with EPA, NOAA NESDIS recently implemented operational aerosol retrievals using the GOES visible channel to produce aerosol optical depth at 30 minute intervals with a 4km spatial resolution in daytime cloud-free conditions. The aerosol retrieval uses the visible channel to sense aerosols and the remaining channels to discern aerosol from clouds. A composite clear sky background is generated over time to estimate the surface reflectance contribution to the top-of-the-atmosphere reflectance. A radiative transfer model is used to convert the TOA observed reflectance to a surface reflectance. The aerosol optical depth of the continental aerosol model in the radiative transfer model is increased until the theoretical reflectance matches the reflectance calculated from the GOES observations. [3]

The first AOT retrievals were limited to one spectral channel.[4] The operational AVHRR algorithm began using two channels in 1995.[5] The accuracy of these retrievals is limited by spectral resolution, inaccurate calibration, and gas absorption contamination.[6] The Moderate Resolution Imaging Spectroradiometer (MODIS) on both the NASA Aqua and Terra Earth Observing System (EOS) satellites has 36 well-calibrated bands with spatial resolution ranging from 250-1000m, enabling daytime cloud-free detection of aerosols with high accuracy and on a nearly global scale over both land and oceans. The aerosol retrieval uses seven well-calibrated channels from the visible to the shortwave IR. The approach uses a look-up table (LUT), which is pre-computed for several values of the aerosol and surface parameters by using a radiative transfer model. The measured spectral reflectances are compared with the LUT reflectances to identify the best solution. [7] Channel selection is optimized to reduce contamination and produce correction information that improves the accuracy of the retrieval. Over the ocean, the measured radiance in channels from 0.55 to 2.13 μm is inverted into the aerosol optical thickness and a volume distribution. Over the land the algorithm uses the mid-IR (2.13 and 3.8 μm) and dark surfaces in the blue and red channels (0.47 and 0.66 μm). Estimated reflectance in the blue and red is used to derive the optical thickness for pixels that are identified to have low reflectance in the mid-IR.[8] Though the algorithms implemented at launch were limited primarily to areas of dark vegetation to minimize uncertainties in the surface reflectance, the algorithms have evolved and exploit the multispectral information to derive optical thickness over additional land surfaces. [9]

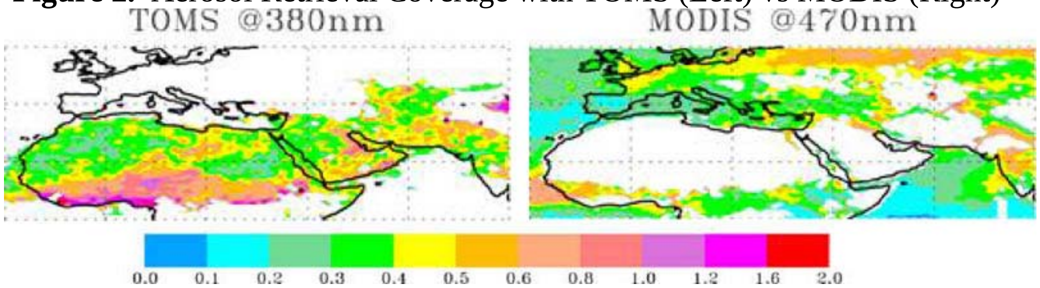
The primary mission of NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is monitoring reflected visible sunlight from the ocean's surface for the derivation of ocean color bio-optical properties. The SeaWiFS ocean color retrieval requires removal of the atmospheric effects and includes an atmospheric correction algorithm that uses two near-infrared bands (765 and 865 nm) to estimate the aerosol optical properties. Therefore, aerosol optical thickness at 865nm over the oceans is a by-product of SeaWiFS ocean color atmospheric correction that has been routinely produced for the past seven years.[10] The Multi-angle Imaging Spectro-Radiometer (MISR) aboard the NASA EOS Terra satellite measures solar reflectance in four spectral bands (red, blue, green, and near infrared), each at nine widely spaced viewing angles simultaneously. Viewing the reflection at different angles with high spatial resolution allows distinguishing different types of aerosols and land surface covers.

The Medium Resolution Imaging Spectrometer (MERIS) on the European Space Agency (ESA) ENVISAT (Environmental Satellite) launched in 2002, has 15 bands from the visible to near infrared and can monitor numerous land, ocean, and atmospheric parameters including aerosol optical depth. A new aerosol retrieval algorithm is under development specifically designed for the hyperspectral ENVISAT MERIS sensor to obtain physical knowledge on the total atmospheric aerosol content, as well as the concentration percentage of four reference aerosol species. An important aspect of the algorithm is that it can be applied to any land zone, mix of vegetation and soil, so it is not focused on the restrictive consideration of dark pixels, like other equivalent aerosol retrieval algorithms do. [11]

UV Absorption/Backscatter

MODIS provides aerosol data with high accuracy and spatial resolution over most of the globe, but challenges in retrieving AOT over highly reflective land surfaces results in regional coverage that must be filled by other means. Though designed to detect ozone using 6 narrow bands in the near ultraviolet region, the Total Ozone Mapping Spectrometer (TOMS) proved capable of detecting UV-absorbing tropospheric aerosols over both land and ocean. The TOMS sensor has flown on numerous domestic and international missions. It was the first instrument to allow observation of aerosols as they cross the land/sea boundary. The UV aerosol retrieval is fundamentally different from that used for visible and near IR, due to a strong Rayleigh scattering signature at the shorter wavelengths and the reduced, less variable surface reflectivity in the UV compared with that at the longer wavelengths. As a result it is possible to detect aerosol clouds over more land surfaces with TOMS, than is possible with the MODIS algorithms currently implemented or the AVHRR aerosol retrievals that are limited to the oceans. However, the TOMS footprint is 50km, while that of the VIR/IR sensors is on the order of a kilometer. The figure below shows a comparison of the MODIS and TOMS coverage. [12]

Figure 2. Aerosol Retrieval Coverage with TOMS (Left) vs MODIS (Right) [12]



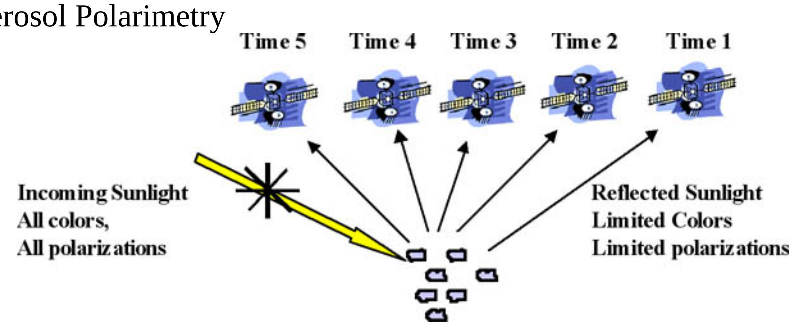
The capability to separate aerosol absorption from scattering effects also allows identification of several aerosol types, ranging from nonabsorbing sulfates to highly UV-absorbing mineral dust, over both land and water surfaces.[13] Daily global images of the TOMS aerosol data reveal a wide range of phenomena such as desert dust storms, forest fires and biomass burning. It is possible to detect global and mesoscale transport of aerosols. TOMS data are used to routinely generate an Aerosol Index, AI, that is related to optical depth. For the current Earthprobe TOMS, AI is defined in terms of the differences between measurements at 331 and 360 nm. The AI produced for the earlier TOMS aboard NIMBUS 7 is based on 340nm and 380nm. [12]

Other ozone monitors also yield tropospheric aerosol data. The GOME, Global Ozone Monitoring Experiment (GOME) flying on the European Space Agency (ESA) Environmental Research Satellite (ERS2) since 1995 and SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY), that encompasses the GOME bands plus much additional capability, both provide reflectance data in atmospheric window channels which are processed into aerosol type and optical depth (at 500nm over ocean areas).[14] The Ozone Monitoring Instrument (OMI) is flying on the NASA Earth Observing System (EOS) Aura mission, which successfully launched in July 2004. OMI aerosol retrieval algorithms have been developed that use 17 wavelengths in the 331-500 nm range over the oceans and two wavelengths in the near UV over land. Studies show it is feasible to distinguish aerosol components (black and organic carbon and sea salt) by deriving their mass ratio to the total particulate matter.[15] Another of the Aura payloads is the High Resolution Dynamics Limb Sounder (HIRDLS) a twenty channel infrared limb-scanning radiometer making measurements at 4° latitude/longitude by 2.5km vertical resolution that provide, among other things, information on concentrations of aerosols in the upper troposphere and stratosphere.

Polarimetry

The incident sunlight becomes partially polarized when it scattered by the atmospheric aerosols, the air molecules, or surface reflections. The strength of the polarization introduced by aerosol scattering and how it varies with scattering angle, depends on the particle size, refractive index, and shape. By observing solar reflectance with polarizing filters at multiple angles and wavelengths, it is possible to determine the properties of the aerosols. Also since the polarization introduced by reflection from land surfaces is insensitive to the wavelength, measurements of the polarization in SWIR, where the aerosol scattering is small if not negligible, can be used to correct for the ground reflection at shorter wavelengths.

Figure 3. Aerosol Polarimetry



The NASA Research Scanning Polarimeter (RSP) is airborne sensor that has successfully demonstrated the capability to use polarimetry to accurately derive aerosol properties and is paving the way for a new generation of space-based aerosol sensors. The only spaceborne polarimeter designed to detect aerosol properties was POLDER (Polarization and Directionality of the Earth's Reflectances) launched on the Japanese Advanced Earth Observing Satellite (ADEOS I & II) missions, both of which suffered premature deaths. Two of POLDER's eight frequencies, 443nm, 765nm are optimized for observing atmospheric aerosols. Though no polarimeter is currently flying, POLDER is planned as the main payload on the future CNES microsatellite PARASOL designed to complement NASA's Earth System Science Pathfinder (ESSP) program. As discussed below under future capabilities, the NPOESS operational mission will include an Aerosol Polarimetry Sensor (APS) dedicated to aerosol detection.

LIDAR

Currently the only method of retrieving aerosol information both night and day is though active sensing such as LIDAR missions. LIDAR also has the advantage of producing information on the vertical distribution of the aerosols. Measurement campaigns have demonstrated the use airborne UV DIAL (Differential Absorption Lidar) systems. A UV-DIAL system measures vertical profiles of ozone and aerosols from near the surface to the upper troposphere along the flight track. A spaceborne system, the NASA Geoscience Laser Altimeter System (GLAS), launched in Jan 2003 aboard the Ice, Cloud and land Elevation Satellite (ICESat) is designed to measure ice, cloud, and atmospheric properties including aerosol vertical structure. Atmospheric backscatter profiles are measured using the 1064 nm and 532 nm channels. The 1064 nm atmospheric measurements are used to profile the heights and vertical distribution of clouds and dense aerosols, resulting in 75 m vertical and 175 m horizontal resolution. The 532 nm atmospheric backscatter measurements are used to measure the vertical distribution of optically thin aerosols during both day and night.[16] Reliability of two of three GLAS lasers was much less than planned and NASA is currently operating the system on an intermittent schedule.

Current Aerosol Data Products

A multitude of historical, current, and future satellite sensors can provide aerosol information. The type of information, the quality, the coverage (global vs land and/or ocean only, day and/or night, clear vs all weather), and the spatial and temporal resolution vary greatly. Furthermore, aerosol data products are not routinely generated for all sensors capable of detecting aerosols. For those that do generate aerosol products, the processing and product distribution timelines differ for science missions than for operational missions and some missions, whether operational or science, charge a fee for data products. The table below summarizes aerosol products currently available from domestic platforms. The grid size of the product is listed; interim data products at the sensor pixel resolution may also be available.

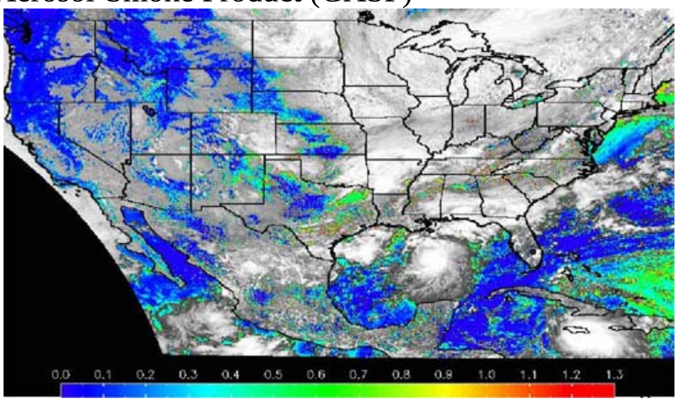
Table 1. Aerosol Product Summary

Sensor	Satellite	Retrieved Parameter	Grid Size	Near Real-Time	Ocean	Land	Day	Night	Comments
OLS	DMSP	N/A							Imagery only
AVHRR	POES	AOT	1 deg	No	Yes	Rsch	Yes		Daily,Weekly/Monthly
VISSR	GOES	AOT	4 km	Yes	Yes	Yes	Yes		
MODIS	Aqua & Terra	AOT	10km		Yes	Some	Yes		AOT is for Dark Vegetation - Rsch Alg for other Land Types Additional Aerosol Products from ASDC
		ASD			Yes	No	Yes		
		Type			No	Yes	Yes		
SEAWifs	SEAWifs	AOT AngC	9km		Yes	No	Yes		
TOMS	Earthprobe	AIndex	50km		Yes	Yes	Yes	No	
OMI	Aura	AOT SSA SO2	13 x 24 km	No	Yes	Yes	Yes		Launch Jul 2004: Products not available yet
MISR	Terra	AOT	17.6km		Yes	Some	Yes		Rsch over homogeneous Sfcs
		AngE SSA APS ASD			Beta	Beta	Beta		
GLAS	ICESat	PBL& A Layer Ht BSctrCS AExtC AOT	7/28km Vertical 76.8 m		Yes	Yes	Yes	Yes	Quicklook Available

AOT = Aerosol Optical Thickness
AIndex = Aerosol Index
AngC/E = Angstrom Coefficent or Exponent
ASP = Aerosol Size Parameter
Type = Aerosol Type
ASD = Aerosol Size Distribution
SSA = Single Scatter Albedo
RelVD = Relative Vertical Distribution
PBL&Alayrer Ht = Planetary Boundary and Aerosol Layer Heights
BsctrCS = Backscatter Cross Section
AextC = Aerosol Extinction CrossSection

NOAA NESDIS produces the only standard operational aerosol product that has been available for the last two decades: a weekly, global composite 1 degree map of equivalent aerosol optical thickness over the ocean retrieved from AVHRR channel-1 radiance measurements. [17] The NASA Goddard Space Flight Center (GSFC) has generated a record of TOMS aerosol optical depth at 380nm covering the periods from January 1979 to April 1993 (Nimbus7-TOMS), and from July 1996 to December 2000 (Earth Probe TOMS). They also provide daily updated global TOMS Aerosol Index maps and the latest 3 day composite image of TOMS Aerosol Index. A TOMS Global Aerosol Hot Spots Page shows close-ups of regions with active fires and smoke emissions from biomass burning (only during fire season).[12] The GOES Aerosol-Smoke Product (GASP) provides aerosol optical depth at 4km spatial resolution and 30-minute intervals. An example is shown in Figure 4 below.[18]

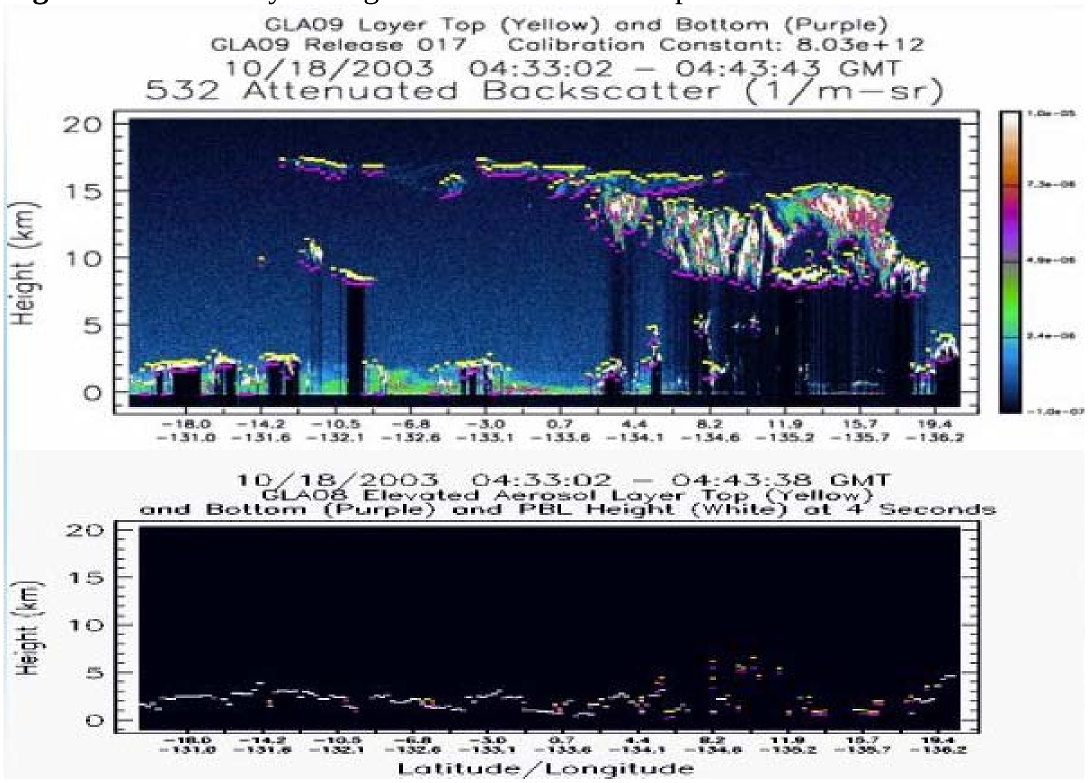
Figure 4. GOES Aerosol-Smoke Product (GASP)



The daily MODIS aerosol product includes aerosol optical thickness globally over oceans and portions of the continents, aerosol size distribution over ocean, and aerosol type is derived over land. The spatial resolution is 10km at nadir from aggregation of 10 x 10 1km pixels.[19] SeaWiFS AOT and Angstrom coefficient data over the oceans are available daily at 9km resolution. A Quicklook product is often available the day after observation with a more refined product later. The NASA SeaWiFS program also generates a MODIS AOT product over the oceans. [20]

GLAS space-borne lidar data are now openly available through the NASA DAAC data distribution system. The planetary boundary layer (PBL) and elevated aerosol layer heights product (GLA08) includes PBL heights, and top and bottom heights of elevated aerosols from 1.5 to 41 km. The aerosol vertical structure product (GLA10) contains the attenuation-corrected cloud and aerosol backscatter and extinction profiles for aerosols. The cloud/aerosol optical depths data (GLA11) contain thin cloud and aerosol optical depths. [21] Realtime quicklook images are available directly from the program office website each day. [22]

Figure 5. GLAS Layer Heights Data Product Example[22]



The NASA Atmospheric Sciences Data Center (ASDC) archives and distributes data in the areas of radiation budget, clouds, aerosols and tropospheric chemistry. The ASDC provides the MISR Level 2 aerosol data product containing aerosol optical depth, aerosol compositional model, ancillary meteorological data, and related parameters mapped to a 17.6 km grid. The aerosol optical depth over heterogeneous surfaces and dark water is also a validated product available from the ASDC. Aerosol optical depth over homogeneous surfaces, aerosol Angstrom exponent, aerosol single-scattering albedo, aerosol particle size and shape fractional amounts are made available at the Beta quality level. The ASDC processes data from the EOS Aqua and Terra CERES (Clouds and the Earth's Radiant Energy System) with the higher-resolution MODIS data to produce clear area aerosol, MODIS land aerosols, and MODIS ocean aerosols mapped to the larger CERES Single Scanner Footprint (SSF). [24]

FUTURE AEROSOL SENSORS IN THE NPOESS ERA

Science satellite missions typically employ state of the art technology; however, revisit time is often limited to one orbit plane and data processing timelines can be on the order of days to months. While adequate for most global climate analyses, such missions are not conducive to supporting applications that require global aerosol information in near real time. Operational satellite missions, such as the POES, GOES, and DMSP are designed to meet such applications. NPOESS will mark a new era in advanced environmental monitoring from space in which predecessor science environmental monitoring and operational weather satellites missions will be merged into an integrated operational environmental observing system.

NPOESS satellites will collect multi-spectral radiometric and other specialized data required to meet 55 Environmental Data Record (EDR) product specifications. The satellites will transmit sensor data shortly after observation to 15 globally distributed receptor sites via a stored mission data link as each satellite comes within view of a site. The data are then be routed to Interface Data Processors (IDPs) located at each of four US Government weather/environmental processing Central facilities (referred to as Centrals) where they are processed into NPOESS products. Flying in three orbital planes, NPOESS will provide frequent data-refresh and rapid-downlink, with ground processing that delivers most products within 30 minutes of observation. NPOESS satellites will also transmit sensor data as they are collected via both High Rate Data (HRD) and Low Rate Data (LRD) direct broadcasts for immediate receipt.

At least three of the eleven baseline sensors aboard NPOESS will provide aerosol information, the VIIRS (Visible Infrared Imaging Radiometer Suite), APS (Aerosol Polarimetry Sensor) and OMPS (Ozone Mapping and Profiler Suite). APS and OMPS will fly in only one of the NPOESS orbit planes, while VIIRS will fly on all three. VIIRS, OMPS and one other NPOESS sensor, the Crosstrack Infrared Sounder (CrIS), will first fly on the NPOESS Preparatory Project (NPP) satellite in 2006. NPP is an NPOESS risk reduction mission that serves as a bridge between NASA's EOS Aqua and Terra and the first NPOESS satellite in 2010. The APS is also slated to fly on a risk reduction flight of opportunity several years prior to launching the first NPOESS.

VIIRS

VIIRS merges the attributes of the current operational DMSP OLS and POES AVHRR sensors with state of the art spectro-radimometer capabilities of the NASA MODIS sensor, and will deliver MODIS-like aerosol products. VIIRS has nine visible/near Infrared channels plus a day/night low light visible band, eight mid-wave IR bands, and 4 long-wave IR bands. The NPOESS VIIRS aerosol optical thickness and particle size parameter algorithms are very similar to those developed for MODIS, but more operationally oriented. Solar-reflected spectral reflectances in multiple channels of visible and near-IR are used to derive the aerosol optical thickness and size distribution simultaneously over land and ocean. Nine spectral bands contribute to the retrieval of AOT over land and ten bands over water. As with MODIS, the VIIRS approach uses a look-up table (LUT), which is pre-computed for several values of the aerosol and surface parameters by using the sophisticated 6S (Satellite Signal in the Solar Spectrum) radiation transfer model. Surface reflectance calculations for VIIRS are updated to include soil dominated surface types. The measured spectral reflectances are compared with the LUT reflectances to identify the best solution.[5] The aerosol model definitions used in the VIIRS retrieval are not identical to those used for MODIS and the VIIRS LUTs have a finer sampling.
Further enhancements are planned that include corrections for BRDF and adjacency effects.

The NPOESS Integrated Program Office (IPO) sponsors Internal Government Studies (IGS) to further advance sensor, algorithm, and data exploitation research. There are currently no space-based nighttime AOT retrievals, but VIIRS does include a Day-Night Band (DNB) designed to provide visible band cloud imagery with a quarter moon illumination. Under an IPO IGS, the Naval Research Laboratory has shown the potential of using VIIRS DNB measurements of scattered moonlight to retrieve AOT at night over oceans. The specification of nighttime AOT would improve temporal coverage to better capture transient aerosol phenomena, provide information on day/night differences of aerosols, and aid in understanding the impact of aerosols on thermal cooling at night with land/sea breezes in coastal regions. [25]

APS

The most recent addition to the NPOESS payload baseline is an instrument dedicated to aerosol detection, the Aerosol Polarimetry Sensor (APS), based on the airborne RSP. APS is being designed to measure the global distribution of natural and anthropogenic aerosols in support of climate change research requirements. As described above, standard aerosol remote sensing relies on changes in measurements of intensity of reflected solar radiation with wavelength and viewing geometry; aerosol models are needed to derive aerosol parameters. Polarimeter measurements allow for unambiguous retrieval of aerosol amount and size by detecting the spectral and angular polarization signature of the reflected radiation. Because small particles polarize light more effectively than large particles, the use of polarization data provides the most significant improvements to the retrieval of fine particulate data.

NASA/GSFC issued a contract to Raytheon Space and Airborne Systems to procure an APS as an NPOESS proof of concept and risk reduction mission. APS aerosol products include: optical thickness; particle size distribution; refractive index, single-scatter albedo and shape. NASA had planned to fly APS on the Glory mission in 2006, but with budget cuts now must identify a later proof of concept/risk reduction flight of opportunity. Regardless, the APS instrument will fly on the NPOESS platform currently scheduled for launch in 2010. APS will be the only source of shape, single scattering, sphericity of aerosols that enable modelers to determine the sign of the aerosol forcing.

The APS instrument will measure the first three Stokes vector elements simultaneously in the following nine spectral bands: 412, 488, 555, 672, 910, 865, 1378,1610, 2250 nm, and will view the earth reflectance from multiple angles. The 488 nm is specifically needed to measure chlorophyll over-water to separate surface radiance and polarization from the atmospheric scatterers, the 910 nm band will measure water vapor, and the 1378 nm will detect cirrus clouds. The remaining bands will be used to fully characterize the aerosols. The wide spectral range, from 412 to 2250 nm, is needed to understand size distributions and to establish the fraction of aerosols that are absorbing rather than reflecting. APS will have a minimum nadir circular pixel size of about 5 kilometers diameter in order not to be overly sensitive to cloud cover. [26]

OMPS

The NPOESS Ozone Mapping and Profiler Suite (OMPS) consists of a nadir system for both total column ozone and profile ozone observations, as well as a limb system for high vertical resolution profile ozone observations. Algorithms for the derivation of other parameters besides ozone have been developed. An interim step in the OMPS ozone retrieval process is the correction for aerosols. An aerosol index is based on the 331-376 nm channels is generated as an interim processing product. Radiative transfer studies performed at NASA/GSFC and Raytheon indicate that the error in retrieved ozone is linearly related to the TOMS aerosol index, AI, defined as the difference between 331 and 360 nm residues. Since the OMPS algorithm does not contain a 331 or 361 nm channel, the difference between the 336 and 377 nm channel residues, R336-377, is used to determine the tropospheric aerosol correction for OMPS. OMPS data processing will also flag detection of sulfate (SO_2) aerosols of 3Dobson units or greater, which can be used in conjunction with VIIRS data to identify sulfates in the NPOESS "Suspended Matter" product.

NPOESS Aerosol Products

In addition to merging the remote sensing technologies of today's science and operational environmental satellite programs, the NPOESS program will make processed aerosol products available to user agencies in less than 30 minutes from the time of observation. Each of the four central IDPs will be capable of processing all 55 NPOESS EDR products and making them available, along with Raw Data Records (RDRs), and calibrated and geolocated Sensor Data Records (SDRs) to the host Centrals and to a Long Term Archive (LTA). Four the of 55 EDRs that NPOESS is required to produce are Aerosol EDRs: Aerosol Optical Thickness, Aerosol Particle Size Parameter (APSP), Suspended Matter (SM), and a fourth EDR that includes Aerosol Refractive Index, Single-Scattering Albedo, and Shape. All aerosol EDRs will be available for clear and daytime conditions. AOT, APSP, and SM and will be produced for all the NPOESS orbits using VIIRS data and will be available within 30 minutes of the time of observation. The fourth EDR is generated with observations from the satellite that carries the APS in addition to the VIIRS and will be provided within 90 minutes.

The NPOESS System Specification defines AOT as the extinction (scattering + absorption) optical thickness along the VIIRS slant path at multiple wavelengths within the 0.4 - 2.4 micron spectral range. Specific more stringent requirements on AOT are levied by the climate users for processing AOT from the satellite with both APS and VIIRS. The AOT will be produced with a spatial resolution of 1.6km over ocean and 9.6km over land. The threshold requirement is a total column measurement with a goal of providing vertical profile information. The Aerosol Particle Size Parameter EDR is characterized in terms of the Ångström wavelength exponent and the effective radius, similar to current science satellite mission aerosol retrievals. The NPOESS Suspended Matter EDR requires that the detected aerosol be typed as dust, sand, volcanic ash, SO2, or smoke. An interim product generated by the OMPS ozone retrieval is used to used to identify SO_2 in the Suspended Matter EDR processing. The fourth aerosol EDR product, consisting of Aerosol Refractive Index, Single-Scattering Albedo, and Shape, is only generated using the NPOESS satellite that carries the APS sensor. An interim step to correct for aerosols in OMPS ozone retrievals is the generation of Aerosol Index along the nadir view and a future enhancement would make this available as a total column Aerosol Index to maintain continuity with the TOMS aerosol product.

The table below summarizes the future NPOESS aerosol related sensors and data products. In contrast to the chart of current sensors, notice that all NPOESS products are available in near real time. Selected foreign and partner missions are also shown in anticipation of greater cooperation on shared data sets, some within operational timelines in the NPOESS era.

Table 2. NPOESS Aerosol Related Sensors and Data Products

Sensor	Satellite	Processed Products	Latency	Ocean HCS	Land HCS	Day	Night	Comments
VIIRS	NPOESS 3 orbit planes	AOT	28min		9.6km		Rsch	
		ASP	28min	1.6km				
		SM	28min		1.6km			
APS	NPOESS 1 orbit	AOT	28min					APS footprint is 5km, APS/VIIRS product can be finer resolution
		ASP	28min	5km	5km TBD	Yes	No	
		SM	28min					
		ARI,SSA,Sh	90min					
OMPS	NPOESS 1 orbit	SO2	28min	50km	50km			
		AIndex	28min					

AOT = Aerosol Optical Thickness SM = Suspended Matter SSA= Single-Scattering Albedo
ASP = Aerosol Size Parameter ARI= Aerosol Refractive Index Sh = Shape

Data Fusion with additional Future Sensors

While state of the art satellite solar backscatter aerosol retrievals exploit multiple radiances and/or multiple viewing geometries, determination of aerosol optical depth, type, and inference of particle size still depends on the assumptions of the aerosol models and fitting the observations to the model. Polarization promises an additional capability. APS sensor measurements will provide a more accurate and complete picture of the types and amounts of aerosols in the atmosphere, but it will only fly on one of the three NPOESS satellites. However, the APS data can be used to reduce errors in VIIRS aerosol retrievals by improving the realism of the aerosol models that are assumed in the VIIRS retrievals. [26]

Satellite data fusion techniques that exploit data from multiple future missions, both domestic and international, will further enhance improved retrievals. Using sensor data fusion introduces additional viewing geometries to reduce the backscatter radiance solution space. Adding polarization yields a unique solution for small particles. Further enhancement can be attained by combining vertical profiles of aerosol extinction from space based LIDAR with the other data to produce simultaneous retrievals of aerosol optical depth, single-scattering albedo, and particle size parameters.[27] The joint NASA/France CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) mission (formerly referred to as Picasso-Cena) is designed to study the role of aerosols and clouds in the climate system. CALIPSO is planned to launch in 2005 as a component of the NASA Earth System Science Pathfinder (ESSP) program and will include a 3-channel backscatter LIDAR in addition to an IR imager and Wide field camera. NASA is planning formation flying amongst the EOS afternoon constellation of science missions satellites: Aqua, CALIPSO, Cloudsat, Aura, and PARASOL (a French micro-satellite containing POLDER). [28]

In the realm of operational missions, the NPOESS IPO will continue data sharing cooperation established under the Initial Joint Polar Satellite System (IJPS) agreement between NOAA and the European Space Agency (ESA). The ESA operational METOP system will include an AVHRR and GOME (or enhanced follow-on versions) during the NPOESS era. The increased data volume, quality, refresh, and timeliness of the NPOESS system and its partner missions will significantly improve satellite characterization of aerosols in the NPOESS era.

Data Assimilation

Aerosols are relatively short-lived in the in the lower troposphere as well as non-homogeneous in both space and time. Even with the addition of multiple space based aerosol detection systems, research to integrate satellite and ground measurements with computer modeling is required to fully characterize the large spatial and temporal variations of aerosols. Techniques will be needed to intervalidate the ever increasing amounts of space based aerosol data and resample all these data sources to coherent and uniform space and time grids. Most space based aerosol retrievals are column quantities; but these data can be integrated with numerical models to specify and forecast a 3-dimensional grid of aerosol distribution that allows understanding of aerosol transport, radiative forcing, and the fine particulate contribution to air pollution. [29]

Currently, satellite-derived aerosol information is not commonly used in numerical models, especially in regional models. Studies to integrate satellite aerosol retrievals into numerical models have demonstrated the potential to significantly improve the performance of aerosol simulations. Assimilation of MODIS aerosol data into the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model produced aerosol optical depths over land in better agreement with ground based AERONET measurements than either the MODIS retrievals or the GOCART simulations alone. [30] Assimilation of GOES geostationary satellite-derived aerosol optical thickness (AOT) into the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) allowed optimal characterization of the spatial and temporal aerosol distribution facilitating a direct comparison with surface observations of downwelling radiative energy fluxes and 2m air temperature. The results indicated that aerosol radiative effects, modeled using the assimilation of GOES AOT, are significant enough to be considered in the simulation of aerosol transport and weather forecast. [31]

The requirements of operational models that can be used to forecast the aerosol contribution to air quality are significantly different from more commonly used global climate or research aerosol models. The NRL (Naval Research Laboratory) Aerosol

Analysis and Prediction System (NAAPS-http://www.nrlmry.navy.mil/aerosol/) is a real-time operational global aerosol transport model used to predict changes in aerosol optical thickness (AOT) and visibility by forecasting the global distribution of tropospheric sulfate, dust, and smoke to benefit the scientific, weather, and regulatory communities. It uses global meteorological fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) data on a 1.1 degree grid, at 6-hour intervals and 24 vertical levels reaching 100 mb. NAAPS does not yet have the capability to directly assimilate aerosol measurements, ground or space-based; rather it estimates aerosol loading based on land categorizations and emissions inventories. NAAPS does use satellite data for terrain categorization and recently, a capability has been demonstrated to use GOES fire hot spot analyses to generate smoke particle fluxes for NAAPS aerosol transport forecasting. [30]

Application of Satellite AOT to PM

Air quality experts are interested in how satellite derived aerosol optical depth specifically relates to ground-based concentrations for regulatory and human health purposes. A recent study sponsored by the joint NASA and EPA project IDEA (Infusing satellite Data into Environmental Applications) demonstrated the use of MODIS aerosol optical depth to determine transport of fine aerosols within the lower troposphere through comparisons between the surface PM2.5 monitors and MODIS aerosol optical depth. Results showed similar spatial patterns in the collocated data sets in the mid-Western US and central Ontario. [2] Another study that compared hourly PM2.5 values from a ground-based monitor in Houston with aerosol optical depth values from the MODIS Terra sensor found good statistical correlation.[31] A study is underway in Europe to demonstrate that both the SeaWiFS and MERIS aerosol products can be converted into PM10 and PM2.5, based on particle density and vertical distribution assumptions.[34]

CONCLUSION

Space-based measurements will be an increasingly valuable tool in the detection, tracking and understanding of aerosols by providing observations over large spatial domains and where ground based measurements are sparse or missing. Numerous satellite missions flying today and planned for the future can retrieve aerosol parameters that can be related to PM concentrations for air quality applications. Most operate in daytime conditions and rely on the detection of solar backscatter. Increasingly sophisticated multi-spectral, multi-angle, polarization, and active sensing methods have been demonstrated and will be employed on future missions. The NPOESS program will merge the remote sensing technologies of today's science and operational environmental satellite programs to provide significantly improved data quality, frequent data refresh, and rapid ground processing to deliver products within operational timelines. Three of the 11 NPOESS sensors will provide data used to retrieve four global aerosol products. Satellite data fusion techniques that exploit data from multiple future partner missions will further enhance improved retrievals. Assimilation of these satellite aerosol retrievals into the mesoscale numerical models has the potential to become a cost-effective method to improve particulate matter forecasting. It is essential that air quality agencies plan now to procure the capability to acquire, display, and assimilate these valuable sources of data into modeling processes to improve particulate matter forecasting into the NPOESS era.

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